



Modelling transient dynamics of a fiber laser with application to deep space optical communications.



George Valley
Aerospace Corporation

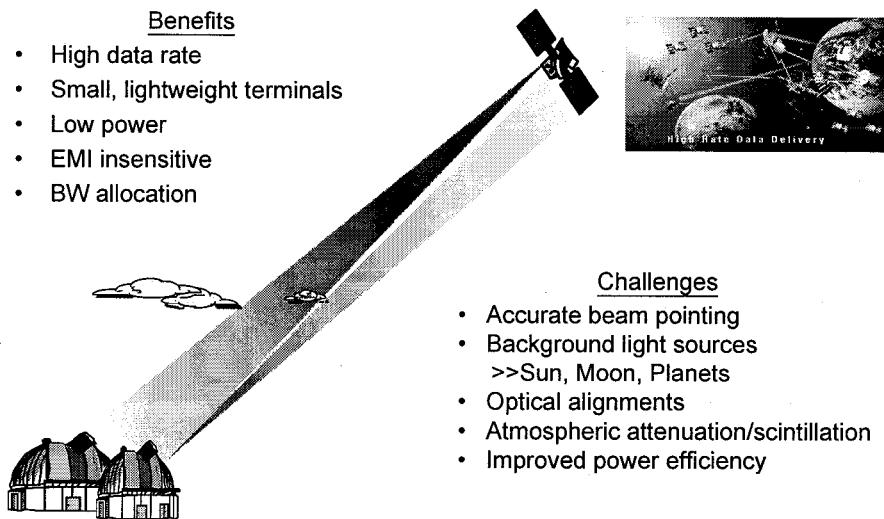
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Motivation: Deep Space Optical Communications

Benefits

- High data rate
- Small, lightweight terminals
- Low power
- EMI insensitive
- BW allocation



Challenges

- Accurate beam pointing
- Background light sources
>>Sun, Moon, Planets
- Optical alignments
- Atmospheric attenuation/scintillation
- Improved power efficiency



Laser Requirements

- High peak powers, kW - MW/pulse, few W average power
- Handle data rates from kbps - Mbps
- Excellent beam quality
- High power conversion efficiency, compact, reliable

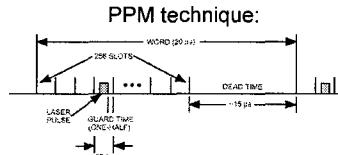
} \Rightarrow DP SS or
Fiber laser

Laser characteristics, eg Mars downlink:

- | | |
|-----------------|--------------------|
| - Wavelength, | 1.06 μm |
| - Average power | 1.5 W |
| - peak power, | 13 kW /pulse |
| - rep rate, | 14 kHz |
| - Pulse width, | 8 ns |

Assumes:

Link range 1.5 AU ($2 \cdot 10^8$ km)
30 cm transmit to 350 cm receive aperture
100 kbps data rate with 8 bit PPM modulation
3 dB link margin

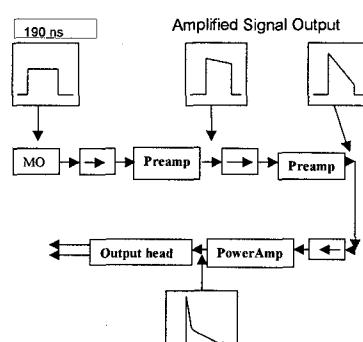
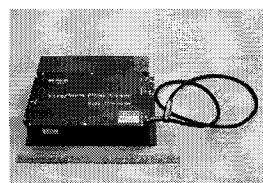


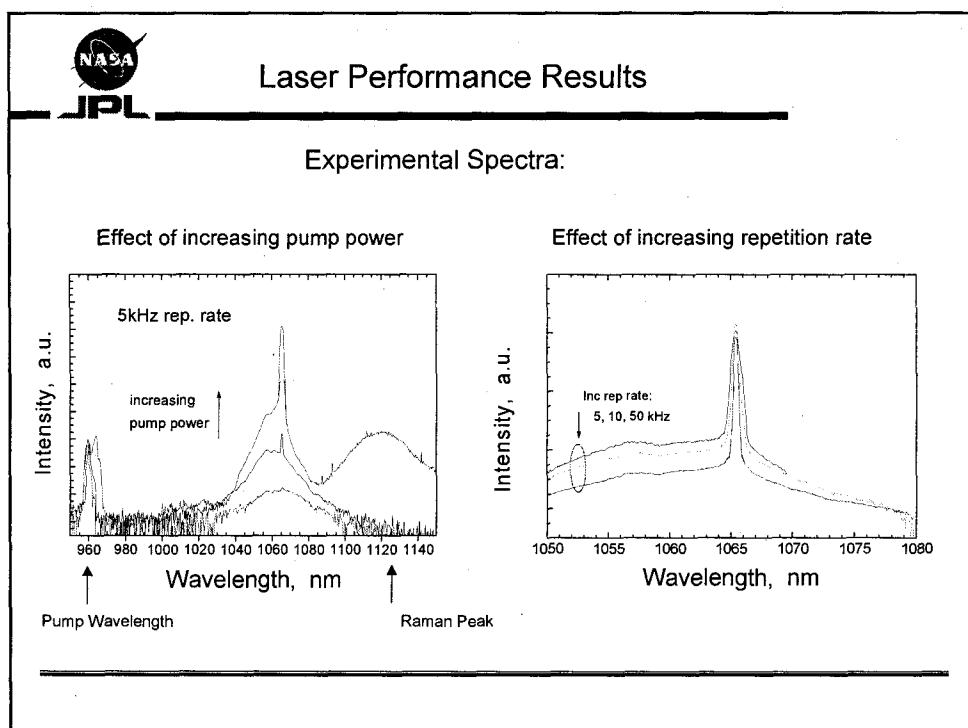
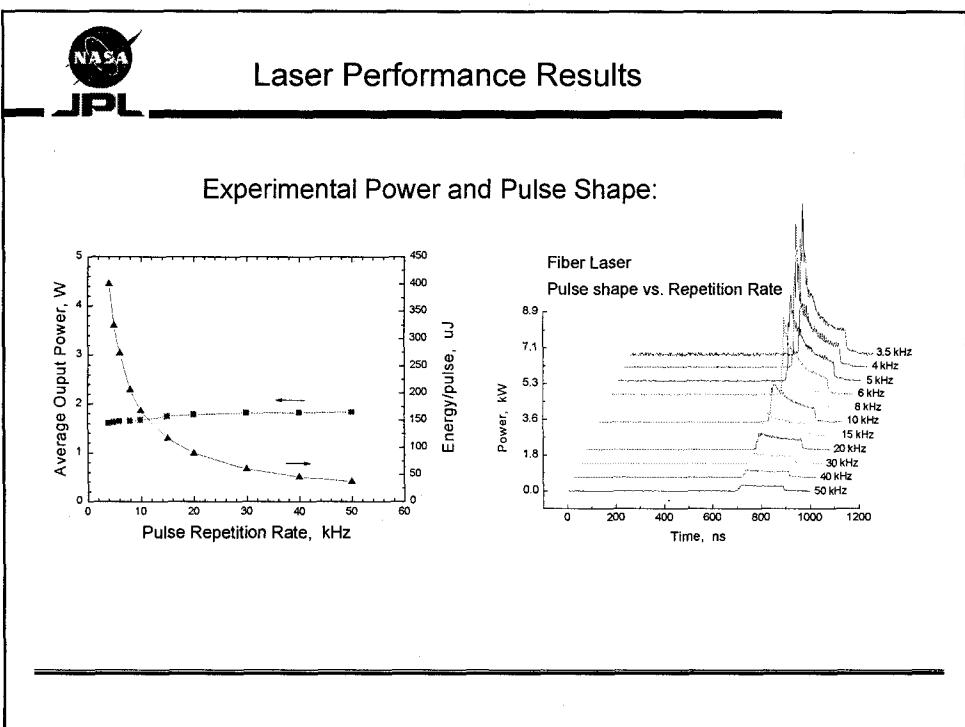
Laser Transmitter

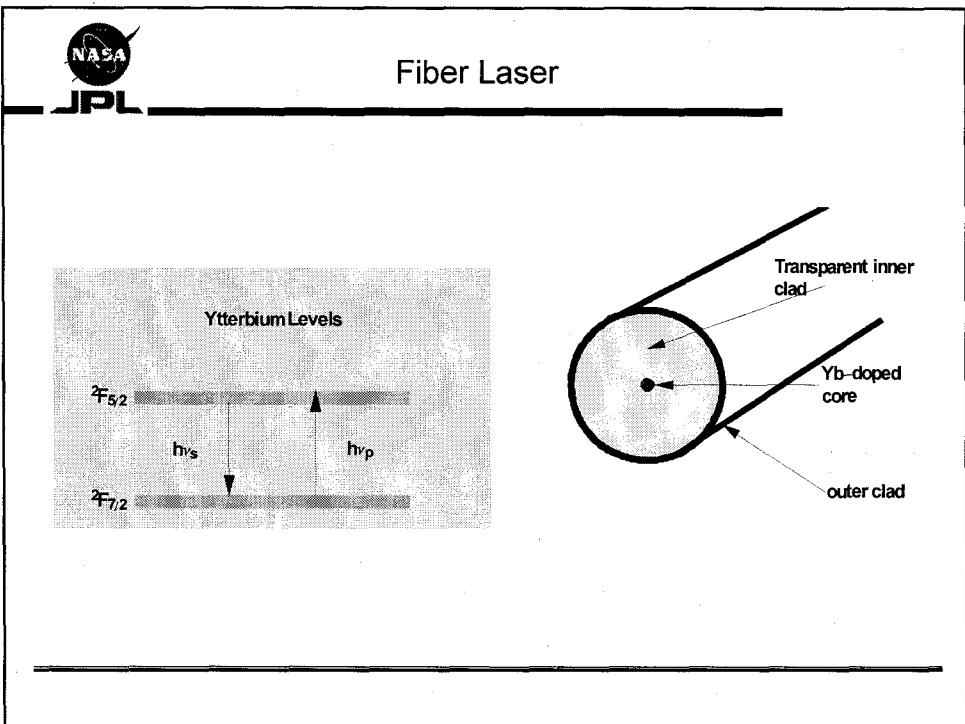
IPG Photonics Developed Yb Doped Fiber Laser

Performance:

- | | |
|--------------------------|-------------------------------|
| • Overall Efficiency | 12 % exc. TEC,
9% with TEC |
| • Wavelength | 1066 nm |
| • Avg. Output power | 1.6 W |
| • Peak Power | 9 kW @ 3.5 kHz
(~400uJ) |
| • Beam quality | $M^2 = 1.8$ |
| • Pulse repetition freq. | 3.5 - 50 kHz |
| • Pulse width | 24 ns @ 4 kHz |
| • Cooling method | passive |







NASA
JPL

Fiber Laser Equations

Fractional Inversion:

$$\frac{\partial n_1(t, z)}{\partial t} = \frac{\sigma_a^P P(t, z)}{h\nu_P A_{\text{dad}}} + \frac{\sigma_a^S S(t, z)}{h\nu_S A_{\text{core}}} - \frac{n_1(t, z)}{\tau} - \frac{(\sigma_a^P + \sigma_e^P) n_1(t, z) P(t, z)}{h\nu_P A_{\text{dad}}} - \frac{(\sigma_a^S + \sigma_e^S) n_1(t, z) S(t, z)}{h\nu_S A_{\text{core}}}$$

Signal Power:

$$\frac{\partial S(z, t)}{\partial z} = (\sigma_a^S + \sigma_e^S) N_{\text{yb}} n_1(t, z) S(t, z) - \sigma_a^S N_{\text{yb}} S(t, z)$$

Pump Power:

$$\frac{\partial P(z, t)}{\partial z} = (\sigma_a^P + \sigma_e^P) \left(\frac{r_{\text{core}}}{r_{\text{dad}}} \right)^2 N_{\text{yb}} n(t, z) P(t, z) - \sigma_a^P \left(\frac{r_{\text{core}}}{r_{\text{dad}}} \right)^2 N_{\text{yb}} P(t, z)$$



Laser Performance Results

Simulation Parameters:

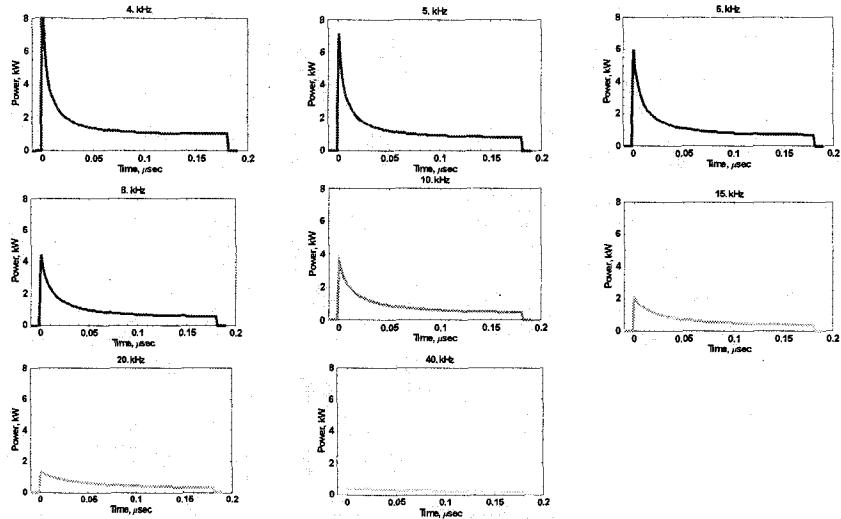
Absorption cross section at pump wavelength
Emission cross section at pump wavelength
Absorption cross section at signal wavelength
Emission cross section at signal wavelength
Lifetime of Yb upper level
Ytterbium number density
Core radius
Clad radius
Pump wavelength
Signal Wavelength

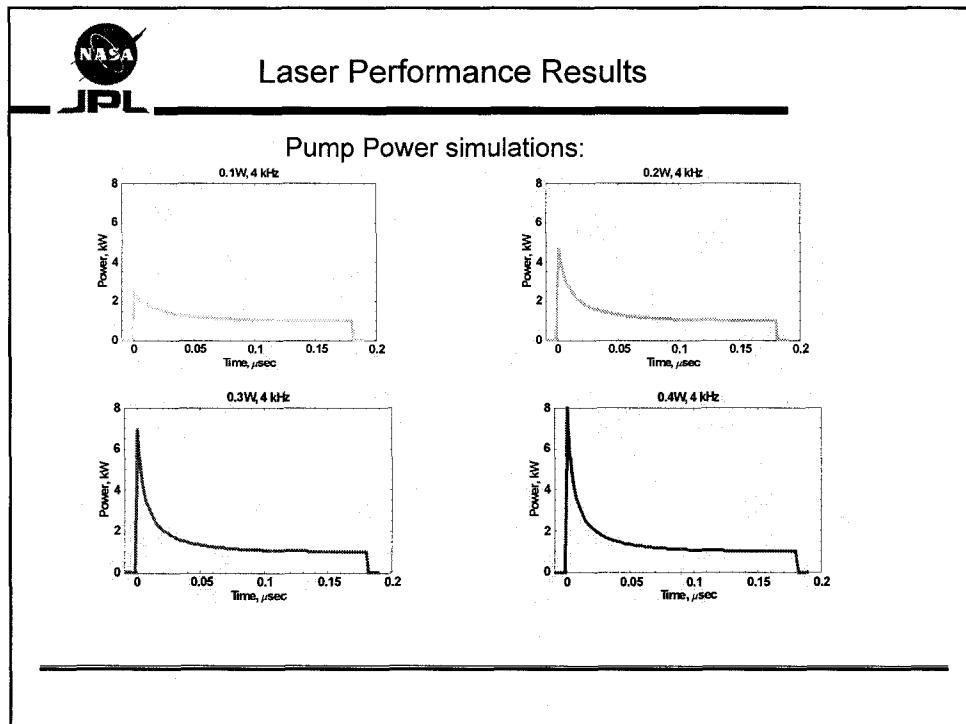
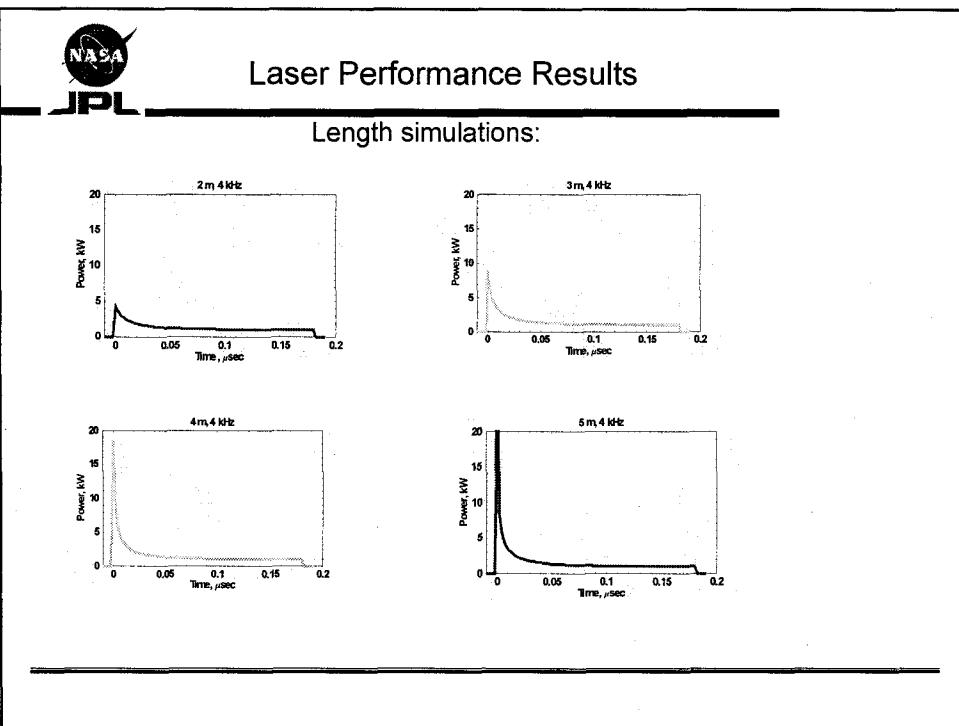
$$\begin{aligned}\sigma_a^P &\sim 10^{-24} \text{ m}^2 \\ \sigma_e^P &\sim 10^{-24} \text{ m}^2 \\ \sigma_a^S &\sim 0 \\ \sigma_e^S &\sim 0.15 10^{-24} \text{ m}^2 \\ t &\sim 1 \text{ ms} \\ N_{\text{Yb}} &\sim 10^{25} \text{ m}^{-3} \\ r_{\text{core}} &= 3.3 \text{ microns} \\ r_{\text{clad}} &= 10 \text{ microns} \\ \lambda_p = c/\nu_p &= 975 \text{ nm} \\ \lambda_s = c/\nu_s &= 1060 \text{ nm}\end{aligned}$$



Laser Performance Results

Simulations:







Summary

- High power fiber laser suitable candidate for optical communications
 - Transient dynamics modeled
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